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SHEAR STRENGTHENING OF REINFORCED CONCRETE BEAMS USING NEAR SURFACE MOUNTED GLASS FIBRE REINFORCED POLYMER

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ABSTRACT

Near Surface Mounted Reinforcement (NSMR) method is a recent strengthening technique based on bonding Fiber Reinforced Polymer (FRP) into grooves on the concrete cover of the elements to be strengthened. In this paper, an experimental program was carried out to assess the effectiveness of the NSMR technique in the shear strengthening of reinforced concrete beams. A number of beams were strengthened in shear using NSM Glass Fibre Reinforced Polymer (GFRP) and tested to analyze the influence of selected test parameters such as the type, spacing, and inclination of the NSM reinforcement on the structural behaviour and failure mode. One beam specimen was strengthened in shear using GFRP sheet as U wrap over the entire shear span by the conventional Externally Bonded Reinforcement (EBR) technique and tested for direct comparison with NSMR technique.

Keywords: Glass fibre reinforced polymer; near surface mounted reinforcement; externally bonded reinforcement; shear strengthening

1. INTRODUCTION

One of the major problems faced by the construction industry today is deterioration of concrete structures. Replacement of such deficient structures incurs a huge amount of public money and time. So, strengthening has become the acceptable way of improving their strength and serviceability. The Fibre Reinforced Polymer (FRP) composite materials play a major role in the area of strengthening and retrofitting of degraded or strength deficient structures. FRP composite materials have a number of advantages when compared to traditional strengthening materials such as steel and concrete jackets. The main advantage of using FRP is that the reinforcement can be arranged according to the loading conditions so that an FRP structure or a component can be optimized for performance. Also, FRP offer excellent corrosion resistance to environmental agents as well as the advantages of high stiffness-to-weight and strength-to-

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weight ratios when compared to conventional strengthening materials. Glass fibres are considerably cheaper than carbon fibres and aramid fibres. Therefore Glass Fibre Reinforced Polymer (GFRP) composites have become popular in many applications. Shear failure is catastrophic and occurs usually without advance warning. Thus, it is desirable that the beam fails in flexure rather than in shear. Deficiencies for shear occur for several reasons, including insufficient shear reinforcement or reduction in steel area because of corrosion, increased service load, and construction defects. To increase the shear resistance of concrete beams, sheets and laminates of FRP are generally applied on the faces of the elements to be strengthened, using an externally bonded reinforcing (EBR) technique. Several researchers have verified that the shear resistance of concrete beams can significantly be increased by adopting the EBR technique. But this technique cannot mobilize the full tensile strength of FRP materials, due to premature debonding from the concrete substrate. Since FRP systems are directly exposed to weathering conditions, negative influences of freeze/thaw cycles and the effect of high and low temperatures should be taken into account in the reinforcing performance of these materials. In addition, EBR systems are susceptible to fire and act of vandalism. A more recent and less investigated method for shear strengthening of RC members involves the use of Near Surface Mounted (NSM) FRP reinforcement, usually in the form of round or square bars or of rectangular bars with large width to thickness ratio called strips. In the NSM method, the reinforcement is embedded in grooves cut onto the surface of the member to be strengthened and filled with an appropriate groove filler such as epoxy paste or cement grout. Use of NSM FRP rods and strips can preclude delamination type of failures frequently observed by using EBR technique.

A number of studies on the performance of FRP as shear reinforcement are reported in the literature. As per Ahmed Khalifia et al. [1] the strengthening technique using CFRP sheets can be used to increase the shear capacity significantly. Andrea Rizzo et al. [2] suggested that the NSM FRP reinforcement significantly enhanced the shear capacity of RC beams also in presence of a limited amount of steel shear reinforcement. De Lorenzis and Teng [3] have discussed the issues raised by the use of NSM FRP reinforcement such as optimization of construction details, models for the bond behavior between NSM FRP and concrete, reliable design models for flexural and shear strengthening and the maximization of the advantages of this technique. They also gave a critical review of existing research in this area, identified gaps of knowledge and outlined directions for further research. The study by Jayaprakash et al. [4] confirmed that the bi-directional CFRP strip strengthening technique contributes shear capacity to reinforced concrete rectangular shear beams. The study also showed that the external CFRP strip acts as shear reinforcement similar to the internal steel stirrups. Hassan et al. [5] investigated the feasibility of using different strengthening techniques as well as different types of FRP for strengthening concrete structures. Test results showed that the efficiency of NSM CFRP strips was three times that of the EBR CFRP strips. Kachlakev and McCurry [6] showed that the addition of GFRP alone for shear was sufficient to offset the lack of steel stirrups and allow conventional RC beam failure by yielding of the tension steel. Sundarraja and Rajamohan [7] have conducted experiments on reinforced concrete beams externally strengthened with GFRP inclined strips as shear reinforcements. The effectiveness of side strips were compared with that of the U-wrap strips. The ultimate loads of beams retrofitted with U-wrapping were greater than the beams retrofitted by bonding the GFRP strips on the sides alone. The test results by Taljsten et al. [8] proved that a very good strengthening effect in shear could be achieved by bonding fabrics to the face of concrete beams. Tarek Hassan et al. [9] showed that the use of NSM CFRP strips substantially increases the stiffness, strength, debonding loads and bond characteristics of concrete beams. Zhichao et al. [10] concluded that the FRP system can significantly increase the serviceability, ductility, and ultimate shear strength of a concrete beam. Thus, restoring beam shear strength by using FRP is an effective technique.

To understand the behavior of Near Surface Mounted GFRP as the shear reinforcement, the following objectives of this study have been set:

- To investigate the shear behavior and modes of failure of RC beams with shear deficiencies before and after strengthening with Near Surface Mounted GFRP.
- To study the effect of various types of NSM reinforcements such as round bars and strips on the shear behavior of the RC beams.
- To study the effect of alignment of NSM reinforcement on the shear behavior of the RC beams.
- To study the effect of spacing of NSM GFRP reinforcement on the shear behavior of the RC beams.
- To compare the NSMR technique with the EBR technique for shear strengthening of RC beams.

2. EXPERIMENTAL PROGRAM

This study involves the implementation of Near Surface Mounted strengthening technique to increase the shear resistance of concrete beams using GFRP. The NSM technique is based on fixing GFRP into pre-cut slits opened in the concrete cover of lateral surfaces of the beams using adhesive. To assess the efficacy of this technique, an experimental program was carried out on reinforced concrete beams failing in shear. One beam was taken as reference beam which is not strengthened. The beams strengthened using NSMR method were classified into *two series* of beam specimens i.e. series S1 and series S2. The first series, series S1 consists of four types of strengthened beam specimens. Two beam specimens each were strengthened with NSM GFRP strips and round bars, each one of them with strips and bars positioned at 90^o and 45^o in relation to the beam axis in the shear span. The second series, series S2 consists of six types of strengthened beam specimens. Three beams each were strengthened with NSM GFRP strips at spacings125mm, 100mm and 75mm c/c measured along the beam axis, each one of them with strips positioned at 90^o and 45^o to the beam axis. One beam specimen was strengthened in shear using GFRP sheet as U wrap over the entire shear span by EBR technique for direct comparison with NSMR technique.

Influence of the types of reinforcement, spacing and alignment of reinforcement on the efficacy of the NSM strengthening technique in terms of enhancement of the shear capacity of the beam and in terms of the exploitation of the FRP tensile strength was analyzed. The study also aims to understand the failure modes, effect of shear strengthening on the load deflection behavior of the strengthened beams.

2.1 Details of specimens

The size of the beam selected for the study was 175mm x 250mm x 1400mm. The beams were designed as shear deficient beams. Three numbers of 16mm diameter bars were provided as tension reinforcement and three numbers of 8mm diameter bars were provided as top reinforcement. Two legged 6mm diameter bars were provided as holding stirrups at both ends of the beam.

Ordinary Portland cement (53 grade), sand passing through 4.75 mm IS sieve and crushed granite stone of maximum size not exceeding 20 mm were used for the concrete mix. The 28-day compressive strength of the concrete cube was 34.88N/mm^2. Steel bars of yield stress 463.75N/mm^2 were used as main reinforcement and steel bars of yield stress 477.45N/mm^2 were used as stirrups. The cover for the longitudinal bars was maintained at 25mm.

All the specimens were cast in horizontal position inside the mould. The beams to be strengthened using NSMR method were cast with precast grooves aligned at 90^o and at 45^o with beam axis. The grooves were provided throughout the shear span at both the lateral faces of the beams which are to be strengthened with GFRP. The dimensions of the grooves were designed such that after strengthening, 2mm uniform thickness of groove filler is ensured around the GFRP strip as well as the GFRP rod.

2.2 Strengthening of specimens

In order to strengthen the shear deficient beams using NSMR method, GFRP strips and GFRP rods were provided at various alignments. The Glass Fibre strips used were Intec FRP strips of tensile strength 750 N/mm^2. Intec FRP strips were supplied as strips of 3mm thickness, 10mm width and 400mm length. Intec FRP strip is a glass fibre composite with bidirectional fibre orientation manufactured using glass fibre woven mat and epoxy resin. The Glass Fibre rods used were Telerod – G of tensile strength 900 N/mm^2. Telerod – G were supplied as rods of 6mm diameter and 400mm length. Telerod – G is a glass fibre composite manufactured by the pultrution process using longitudinal glass fibres and epoxy resin.

The GFRP strips and rods were provided at 90^o and 45^o with the beam axis at the lateral faces for the shear strengthening of the beams. Inorder to apply GFRP, the precast grooves on the lateral surface of the beams were made rough and then cleaned properly using a wire brush. Then the grooves were filled half way with the groove filler. The groove filler used is Conbextra EP10 which is the medium for the transfer of stresses between the GFRP and the concrete. Conbextra EP10 is a high strength epoxy resin grout designed for grouting of gap widths of 0.25 to 10mm. It is an all liquid system consisting of base and hardener. The surface of the GFRP strips and GFRP rods were roughened for ensuring proper bond between GFRP and the groove filler. Then GFRP is inserted into the groove so the groove filler flows around the GFRP. Then the surface is leveled and smoothened. Then the strengthened beams were left to cure in air for seven days before testing.

Inorder to strengthen the shear deficient beams using EBR technique, U wrap of GFRP sheet of size 675mm x 400mm x 1.5 mm were provided over the entire shear zones. The GFRP used for the EBR application was Nitowrap EP of tensile strength 3400N/mm^2.The designations of all strengthened beam specimens are as shown in the Table 1.

2.3 Testing of specimens

All the beam specimens were tested on a beam testing machine with load controlling capabilities, having a maximum load capacity of 300T. The beam specimens were simply supported with a span of 1200mm. The beam specimens were tested under two-point loading. The deflections at mid-span and one-third span were measured at regular intervals of 0.5T of loading using dial gauges having least count of 0.01mm.

Table 1: Designation of strengthened beam specimens

Series	**Beam designation**	**Provision of GFRP**	**Remarks**
-	CB	No GFRP	Control specimen
Series S1	BR90E	6mm diameter GFRP rods aligned at 90^{o} with beam axis at 100mm c/c spacing	Shear strengthened beam (NSMR)
	BR45E	6mm diameter GFRP rods aligned at 45^{o} with beam axis at 100mm c/c spacing	Shear strengthened beam (NSMR)
	BS90E	3mm x 10mm GFRP strips aligned at 90^{o} with beam axis at 100mm c/c spacing	Shear strengthened beam (NSMR)
	BS45E	3mm x 10mm GFRP strips aligned at 45^{o} with beam axis at 100mm c/c spacing	Shear strengthened beam (NSMR)
Series S2	BS90E125	3mm x 10mm GFRP strips aligned at 90^{o} with beam axis at 125mm c/c spacing using epoxy groove filler	Shear Strengthened Beam (NSMR)
	BS45E125	3mm x 10mm GFRP strips aligned at 45^{o} with beam axis at 125mm c/c spacing using epoxy groove filler	Shear strengthened beam (NSMR)
	BS90E100	3mm x 10mm GFRP strips aligned at 90^{o} with beam axis at 100mm c/c spacing using epoxy groove filler	Shear strengthened beam (NSMR)
	BS45E100	3mm x 10mm GFRP strips aligned at 45^{o} with beam axis at 100mm c/c spacing using epoxy groove filler	Shear strengthened beam (NSMR)
	BS90E75	3mm x 10mm GFRP strips aligned at 90^{o} with beam axis at 75mm c/c spacing using epoxy groove filler	Shear strengthened beam (NSMR)
	BS45E75	3mm x 10mm GFRP strips aligned at 45^{o} with beam axis at 75mm c/c spacing using epoxy groove filler	Shear strengthened beam (NSMR)
-	BUW	GFRP sheet provided as U wrap over the shear span of the beam.	Shear strengthened beam (EBR)

3. RESULTS AND DISCUSSION

In this section the observations during testing and the analysis of the results are briefly described.

3.1 Cracking pattern and failure mode of specimens

The first crack load and ultimate load for the test specimens are shown in Table 2. The cracking patterns of test specimens in the first and second series of specimens are shown in Figure 1 and Figure 2.

Table 2: First crack load and ultimate load of the beam specimens

Beam designation	**First crack load**		**Ultimate load**		**Ultimate shear**		**Failure mode**
	Load (kN)	**Ratio of increase**	**Load (kN)**	**Ratio of increase**	**(kN)**	**% increase**	
CB	83.39	-	161.87	-	80.94	-	Shear failure
BR90E	142.25	1.71	235.44	1.45	117.72	45.44	Shear failure
BR45E	122.63	1.47	220.73	1.36	110.37	36.36	Shear failure
BS90E	147.15	1.76	259.97	1.61	129.99	60.60	Shear failure
BS45E	166.77	2.00	279.59	1.73	139.80	72.72	Shear failure
BS90E125	166.77	2.00	294.3	1.82	147.15	81.80	Shear failure
BS45E125	127.53	1.53	245.25	1.52	122.63	51.51	Shear failure
BS90E100	161.87	1.94	284.89	1.76	142.45	75.99	Shear failure
BS45E100	152.06	1.82	274.68	1.70	137.34	69.68	Shear failure
BS90E75	147.15	1.76	240.35	1.48	120.18	48.48	Shear failure
BS45E75	176.58	2.12	299.21	1.85	149.61	84.84	Shear failure
BUW	93.2	1.12	215.82	1.33	107.91	33.32	Shear failure

During loading of the control beam, diagonal shear cracks initiated at the center of the shear span, at about mid-height of the beam. As the load increased, the first shear crack propagated and one more shear crack formed within the shear span. These cracks widened and propagated until failure resulted.

In series S1, beams BR90E and BS90E showed a similar evolution of the cracking pattern and similar failure mechanism. The first diagonal shear crack appeared in the shear span, at about mid-height of the beam. On continued loading, the cracks propagated towards the adjacent epoxy-filled groove without crossing the epoxy. In these beams, close to failure, these cracks widened and propagated up to the point of application of the load. Beam BR45E failed by debonding of the GFRP rod. During loading of this beam, debonding took place at the rod-epoxy interface. This shows improper bonding between the rod and the adhesive and also shows the inadequacy of the surface treatments of the rod. Beam BS45E failed by the rupture of the GFRP strip within the groove. Except for the beam BR45E, at failure the NSM reinforcement appeared still well bonded to the concrete side covers that had separated from the beam core. The GFRP strips showed no signs of debonding in any of the beam specimens.

Figure 1. Crack pattern of specimen in series S1

In series S2, beam BS90E125 failed by development of shear crack and then flexural cracks followed by the crushing of concrete in the compression zone. At first diagonal shear crack appeared in the shear span, at mid-height of the beam. This crack propagated towards the adjacent epoxy-filled groove. Then close to failure, this crack widened and propagated up to the point of application of the load. Then three flexural cracks developed at the tension side of the beam followed by the failure of beam due to crushing of concrete at the compression side. Thus here, a transition from the catastrophic shear failure to friendly flexural failure mode was obtained. Beams BS45E125 and BS45E100 failed by the rupture of the GFRP strip within the groove. The first diagonal shear crack appeared in the shear span, at about one-third height of the beam. On loading, more shear cracks became gradually visible on the concrete surface between adjacent epoxy filled grooves. Close to failure, the developed first shear crack widened and propagated up to the point of application of the load followed by the rupture of the GFRP strip within the groove. In beam BS90E100, the first diagonal shear crack appeared in the shear span, at about mid-height of the beam. This crack propagated towards the edges of the adjacent epoxy-filled grooves on both sides of the crack. Then close to failure, this crack widened and propagated up to the point of application of the load. In beam BS90E75 also the first diagonal shear crack appeared in the shear span, at about mid-height of the beam. On loading, more shear cracks became gradually visible on the concrete surface between adjacent epoxy filled grooves. These cracks propagated towards the edges of the adjacent epoxy-filled grooves on both sides of the crack. In this beam, close to failure, the first shear crack widened and propagated up to the point of application of the load. Beam BS45E75 failed by the crushing of concrete in the compression zone. At first hairline cracks appeared in the shear span of the beam. These hairline cracks propagated towards the point of application of the load without widening. Then a number of flexural cracks developed at the tension side of the beam within the flexural zone followed by the failure of beam due to the widening of these cracks and crushing of concrete at the compression side. Thus here also, a transition from the catastrophic shear failure to friendly flexural failure mode was obtained. At failure, for the all the beams, the NSM strips appeared still well bonded to the concrete side covers that had separated from the beam core. No sign of debonding was observed in any of the beam specimens.

Beam BUW failed by debonding of the GFRP sheet from the concrete surface. During loading of this beam, evolution of the shear cracking pattern could not be seen due to the presence of external wrapping, but the final pattern was observed after failure by removing the debonded sheet. A widened shear crack was observed in the shear span, when the sheet was removed.

Figure 2. Crack pattern of specimen in series S2

3.2 Load Deflection Behaviour

The load-deflection plots for all the tested beam specimens in series S1and S2 are as shown in Figure 3 and Figure 4. All the strengthened beam specimens showed better load deflection characteristics than the control beam specimens.

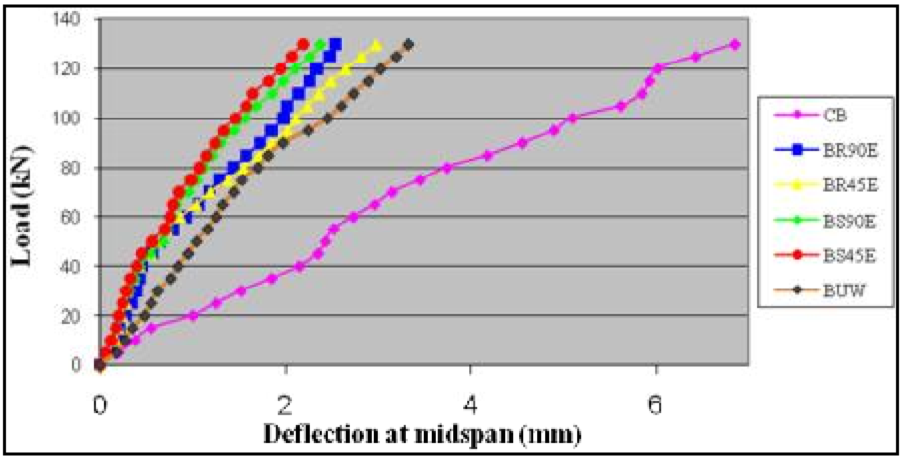

Figure 3. Load deflection plot of beam specimens in series S1

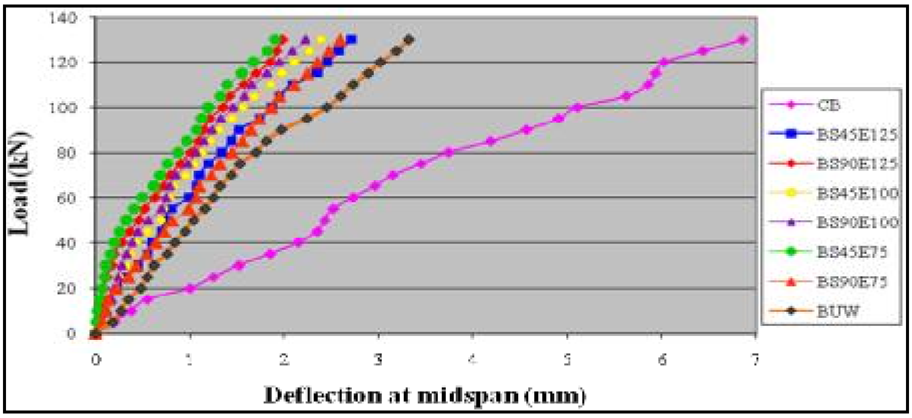

Figure 4. Load deflection plot of beam specimens in series S1

3.3 Discussion

The effect of the type of the NSM reinforcement on shear strengthening can be examined by comparing the test results of beam specimens in series S1. The difference in shear capacity is significant. The beam specimens with NSM strips have higher ultimate loads than those with NSM round rods. This could be because of the bond slip behavior of NSM rods being slightly stiffer than that of the NSM strips; as the rods are stiffer than the strips here. Stiffer local bond slip behavior generates higher bond shear stresses and this may accelerate debonding. At failure, the NSM strips appeared still well bonded to the concrete side covers that had separated from the beam core. Hence in the test series S1 reported herein, the rectangular strips of GFRP which were less stiff are found to be better than the round bars in shear strengthening of RC beams. The effect of the spacing and alignment of the NSM reinforcement on shear strengthening can be examined by comparing the test results of beam specimens in series S2. The spacing between the strips in the orthogonal direction in all the beams were calculated and the beams were arranged in the decreasing order of the spacing as shown in Table 3.

It can be seen from the table that, as the spacing between the strips in the orthogonal direction decreases, the shear capacity of the strengthened beams decreases up to an extend and then increases. As the spacing between the strips in the orthogonal direction is decreased the interaction between the bond stresses around adjacent GFRP strips gets strengthened and hence the formation of failure pattern is accelerated. Thus, decreasing the spacing between the strips or increasing the inclination of the strips do not benefit the shear capacity of the beams. In both the cases, the reduced distance strengthens the interaction between the bond stresses around adjacent strips and hence accelerates the formation of failure pattern. But this trend is reversed when the spacing between the GFRP strips was decreased from 106 mm to 88mm. Thereafter steady increase in the strength was observed with decreased spacing between the strips in the strengthened beam specimens *i.e.*, for the beam specimens BS45E125, BS45E100 and BS45E75. Here, the beneficial effect due to decreased spacing is predominant over the adverse effect due to interaction. Thus, it is the spacing between the strips in the orthogonal direction which governs the shear capacity of the strengthened beam.

Table 3: Shear capacity of the beam specimens in series S2

Beam designation	Spacing between strips in the orthogonal direction (mm)	Ultimate load (kN)	Applied shear (kN)	% Increase in Shear capacity
BS90E125	176.78	294.3	147.15	81.80
BS90E100	141.42	284.89	142.45	75.99
BS90E75	106.07	240.35	120.18	48.48
BS45E125	88.39	245.25	122.63	51.51
BS45E100	70.71	274.68	137.34	69.68
BS45E75	53.03	299.21	149.61	84.84

4. CONCLUSIONS

From the study conducted on the shear strengthening of concrete beams using GFRP in various types like sheets, strips and rods in various alignments and spacings; the following conclusions were drawn:

- GFRP sheets, strips and rods are found to be effective in shear strengthening of concrete beams.
- The strengthened beams showed improvement in terms of first crack load, ultimate load and deflection characteristics when compared to that of the control beam.
- The overall performances of all the strengthened beams were superior to that of the control beam.
- The use of NSM reinforcement was more efficient than externally bonded reinforcement in terms of exploitation of the FRP tensile strength. This is due to the early debonding of the externally bonded reinforcement from concrete.
- The GFRP rectangular strips were found to be more effective in strengthening than the stiffer GFRP circular rods.
- It is the spacing between the strips in the orthogonal direction which governs the shear capacity of the strengthened beam.
- Decreasing the spacing between the strips or increasing the inclination of the strips do not benefit the shear capacity of the beams. In both the cases, the reduced distance strengthens the interaction between the bond stresses around adjacent strips and hence accelerates the formation of failure pattern. But this trend ceases after a particular spacing and thereafter the shear capacity increases with the decreased spacing between the strips.
- The beam specimen strengthened with EBR showed an increase of 1.33 times in ultimate load, when compared to the control beam specimens. Whereas those strengthened with NSM reinforcement showed an increase varying between 1.36 to 1.85 times when compared with the control beam specimens.
- The ultimate shear and bending capacities of all the strengthened beams were more than that of the control beam specimens. The beam specimen strengthened with EBR attained an increase of 33.3% in the shear capacity, when compared to the control beam specimens. Whereas those strengthened with NSM reinforcement showed an increase varying from 36.4% to 84.8%.
- All the strengthened beam specimens showed better load deflection characteristics than the control beam specimens. For any particular load, the deflection of all the strengthened beam specimens was lesser than that of the control beam specimens.
- The beam specimens strengthened with NSM reinforcements showed better deflection characteristics when compared to the beam specimens strengthened with externally bonded reinforcement.
- The GFRP strips showed no signs of debonding in any of the strengthened beam specimens. At failure the NSM strips appeared well bonded to the concrete side covers that had separated from the beam core.
- For the beam specimens BS90E125 and BS45E75, a transition from shear to flexure was observed in the failure mode. Thus transition from the catastrophic shear failure

mode to friendly flexural failure mode can be obtained by using the NSMR strengthening technique.

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